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# RESEARCH MEMORANDUM

COMPARISON OF EXPERIMENTAL WITH THEORETICAL  
TOTAL-PRESSURE LOSS IN PARALLEL-WALLED  
TURBOJET COMBUSTORS

By Ralph T. Dittrich ✓

Lewis Flight Propulsion Laboratory  
Cleveland, Ohio

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NATIONAL ADVISORY COMMITTEE  
FOR AERONAUTICS

WASHINGTON

January 9, 1957

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## NATIONAL ADVISORY COMMITTEE FOR AERONAUTICS

RESEARCH MEMORANDUM

## COMPARISON OF EXPERIMENTAL WITH THEORETICAL TOTAL-PRESSURE

## LOSS IN PARALLEL-WALLED TURBOJET COMBUSTORS

By Ralph T. Dittrich

## SUMMARY

An experimental investigation of combustor total-pressure loss was undertaken to confirm previous theoretical analyses. The investigation considered the effects of geometric and flow variables and of heat addition on the total-pressure-loss coefficient of a parallel-wall turbojet combustor.

The results indicate that a reasonable estimate of cold-flow total-pressure-loss coefficient may be obtained from the theoretical analyses. Calculated values of total-pressure loss due to heat addition alone show good agreement with experimental data if there is no flame ejection from the liner at the upstream air-entry holes. When flame ejection occurs, the total-pressure loss is abnormally high because of recirculation of, and heat addition to, the gases in the annular passage. Factors that appear to cause flame ejection are (1) relatively large liner total hole area, (2) a large outlet-to-inlet temperature ratio, and (3) a low reference Mach number.

## INTRODUCTION

Total-pressure losses of the gases flowing through an aircraft jet-engine combustor result mainly from sudden expansions or contractions in flow area, jet mixing, wall friction, and the addition of heat to the gases. While some pressure loss is unavoidable and some is utilized to obtain efficient combustion, these losses reduce engine thrust and the flight range of the aircraft (refs. 1 and 2) and, hence, must be minimized.

A convenient method for predicting total-pressure loss would facilitate the design of aerodynamically efficient turbojet combustors. Methods for the rapid calculation of pressure losses due to heat addition alone are presented in references 3 to 7. The calculation of combustor over-all total-pressure loss is normally a complex process.

Reference 8 presents a simplified method, developed from a theoretical analysis of combustor aerodynamics, for calculating pressure losses. This reference also presents generalized curves showing the variation in total-pressure loss with combustor-geometry and flow conditions. The present investigation provides experimental data indicating the validity of the theoretical data presented in reference 8.

Experimental pressure-loss data were obtained with a parallel-walled, tubular research combustor for ranges of flow conditions and geometric variables similar to those considered in reference 8. In both investigations the major geometric variables studied were the liner total open hole area and the cross-sectional area of the liner relative to that of the outer shell. Pressure-loss data obtained without heat-addition in the liner are compared with the calculated values of reference 8. Limited data were also obtained with heat addition in the liner. The pressure losses due to the heat addition alone are compared with values calculated by the methods of both references 3 and 8.

#### SYMBOLS

$A_{h,t}$	total liner open hole area, sq ft
$A_L$	cross-sectional area of liner, sq ft
$A_r$	outer-shell cross-sectional area; reference area, sq ft
$M_r$	Mach number based on inlet condition and reference area
$P_A'$	local total pressure in annulus, lb/sq ft
$P_1$	combustor-inlet total pressure, lb/sq ft
$\Delta P/q_r$	total-pressure-loss coefficient
$P_A$	local static pressure in annulus, lb/sq ft
$P_L$	local static pressure in liner, lb/sq ft
$q_r$	dynamic pressure based on outer-shell cross-sectional area and inlet conditions, lb/sq ft
$Re_r$	Reynolds number based on outer-shell cross-sectional area and inlet conditions
$T_1$	combustor-inlet total temperature, $^{\circ}R$

$T_o$  combustor-outlet total temperature,  $^{\circ}R$

$w_a$  airflow rate, lb/sec

## APPARATUS AND PROCEDURE

### Combustor

A schematic diagram of the tubular research combustor installation is presented in figure 1. The combustor was connected to the laboratory pressurized air and exhaust systems. The airflow rate and pressure were regulated by remote-controlled valves located upstream of the plenum chamber and downstream of the combustor test section. Airflow was metered by calibrated flow nozzles having throat diameters of either 3.746 or 4.543 inches. These nozzles were located downstream of the plenum chamber (fig. 1).

Details of the research combustor are shown in figure 2. The liner consisted of a 6.0-inch-outside-diameter, 0.031-inch-wall metal tube having eight uniformly distributed rings of 1.375-inch-diameter holes. In each ring six holes were equally spaced around the circumference. The liner total open hole area was varied by covering various rings of holes with strips of 0.008-inch-thick metal and sealing them with masking tape. The liner dome had no air-entry holes and was streamlined to provide a uniform velocity distribution at the annulus entrance. Three different diameter outer shells were used. The dimensions of the various liner and outer-shell combinations tested are listed in the following table:

Liner diam., in.	Liner cross-sectional area, $A_L$ , sq ft	Shell diam., in.	Shell cross-sectional area, $A_r$ , sq ft	$A_L/A_r$	Rings of liner holes open	Total liner hole area, $A_{h,t}$ , sq ft	$\frac{A_{h,t}}{A_r}$	$\Delta P/q_r$ against $M_r$ , figure
6.005	0.1967	8.48	0.392	0.502	8	0.495	1.26	4(a)
					6	.371	.95	(b)
					3	.186	.47	(c)
					2	.124	.32	(d)
		7.74	0.327	0.602	8	0.495	1.51	4(e)
					6	.371	1.14	(f)
					3	.186	.57	(g)
					2	.124	.38	(h)
		7.14	0.278	0.708	8	0.495	1.78	4(i)
					6	.371	1.34	(j)
					3	.186	.67	(k)
					2	.124	.45	(l)

For tests with heat addition in the liner, a fuel nozzle supplying gaseous propane fuel and an ignition plug were installed in the liner.

### Instrumentation

Total-pressure surveys upstream and downstream of the combustor (stations 1 and 3, fig. 2) were made with rakes having ten total-pressure tubes each, the tubes being located along centerlines of five equal areas. Total-pressure surveys were also made at the annulus entrance (station 2, fig. 2) by means of a probe having a 0.020-inch-diameter tip. This probe was moved radially across the annular passage.

Combustor-inlet air temperature was measured by a single thermocouple located between the airflow nozzle and the combustor. For tests with heat addition in the combustor, 28 thermocouples were installed immediately downstream of pressure-measuring station 3 (fig. 2). These thermocouples were equally spaced along centerlines of four equal circular areas. By means of a suitable switching arrangement, either individual measurements or an average of the 28 thermocouples could be obtained.

### Procedure

Pressure-loss data were obtained with all configurations at cold-flow conditions. A range of reference Mach number was investigated by varying the inlet pressure in the range from 850 to 5600 pounds per square foot absolute while maintaining the airflow rate constant at a nominal value of 4 pounds per second. With some configurations additional data were obtained at airflow rates of 2 and 6 pounds per second in order to vary Reynolds number. Pressure loss due to heat addition was studied with a configuration that was selected from the generalized curves of reference 8 for low-pressure-loss characteristics. The inlet air temperature was approximately 75° F for all tests.

The pressure-loss coefficient  $\Delta P/q_r$  is defined as the ratio of the difference in average total pressures between stations 2 and 3 to the reference dynamic pressure. The inlet total pressures, however, were measured at station 1 and corrected to station 2 because the average total pressure was more readily determined at the large cross-sectional area at station 1 (numerical average) than at the small annular area of station 2 (weighted average). The loss in average total pressure across stations 1 and 2 was measured for the various outer shells (fig. 3), and the average total pressure at station 2 was obtained by correcting station 1 measurements by this pressure loss (fig. 3). The reference dynamic pressure  $q_r$  was calculated on the basis of the air density at station 2 and the cross-sectional area of the outer shell.

## RESULTS AND DISCUSSION

## Cold-Flow Pressure Loss

Experimental data showing the variation of total-pressure-loss coefficient  $\Delta P/q_r$  with reference Mach number  $M_r$  for the various configurations investigated are compared in figure 4 with theoretical pressure-loss data for like configurations. The theoretical data calculated both with and without annulus wall friction were obtained from figures 9 and 11 of reference 8. The calculations with annulus wall friction (ref. 8) assumed a friction factor of 0.005 and an outer-shell length-to-diameter ratio of 4. The configurations used in the present investigation have outer-shell length-to-diameter ratios ranging from 4.4 to 5.2.

The effect of  $M_r$  on  $\Delta P/q_r$  was least for a configuration having a cross-sectional area ratio  $A_L/A_r$  of 0.502 and a liner total hole area ratio  $A_{h,t}/A_r$  of 1.26 (fig. 4(a)). The effect of  $M_r$  increases with both an increase in  $A_L/A_r$  (fig. 4(j)) or a decrease in  $A_{h,t}/A_r$  (fig. 4(d)). The reference Mach number of conventional turbojet combustors is generally within the range from 0.025 to 0.08. Figure 4 shows that within this range the effect of  $M_r$  on the  $\Delta P/q_r$  is small for all configurations investigated.

A comparison of the theoretical with the experimental values of  $\Delta P/q_r$  (fig. 4) shows that the calculated values including annulus wall friction are within 17 percent of but are generally higher than the experimental data. Better agreement with experimental data for  $A_L/A_r$  of 0.502 and 0.602 is shown by calculated values that neglect annulus wall friction. For some combustor configurations the calculated  $\Delta P/q_r$  curves were not extended to the higher values of  $M_r$  because local Mach numbers approached unity.

Several configurations were tested at airflow rates of 2, 4, and 6 pounds per second (figs. 4(a), (e), and (i)). Within experimental error, the data fall on single curves, indicating that, for the ranges of operating conditions investigated, reference Reynolds number had a negligible effect on  $\Delta P/q_r$ .

The effect of liner hole distribution on  $\Delta P/q_r$  for an  $A_{h,t}/A_r$  of 0.38 is shown in figure 4(h). A liner having all air-entry holes at the downstream end had a  $\Delta P/q_r$  approximately 10 percent greater than that of a liner having all entry holes at the upstream end or one having an air-entry hole area divided between upstream and downstream ends. Hence, liner hole distribution has a minor effect on total-pressure-loss coefficient.

The effect of the geometric variables on the pressure-loss coefficient is shown in figure 5, wherein the data of figure 4 are cross-plotted for values of  $M_r$  of 0.05 and 0.15. The total-pressure-loss coefficient  $\Delta P/q_r$  approaches a minimum value for an  $A_L/A_r$  of 0.502 as the  $A_{h,t}/A_r$  exceeds a value of 1.0. The  $\Delta P/q_r$  increases rapidly with an increase in  $A_L/A_r$  above approximately 0.602 or a decrease in  $A_{h,t}/A_r$  below 1.0. A comparison of figures 5(a) and (b) shows that an increase in  $M_r$  increases the effect of geometric variables on the total-pressure-loss coefficient. Similar trends are shown by the theoretical pressure-loss curves in figure 5.

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#### Pressure Loss with Heat Addition

The hot-flow pressure-loss data presented in figure 6 were obtained with a configuration having a cross-sectional area ratio  $A_L/A_r$  of 0.602 and a liner hole area ratio  $A_{h,t}/A_r$  of 1.14. Although cold-flow tests showed that minimum total-pressure loss was obtained with a configuration having an  $A_L/A_r$  of 0.502, the analysis of reference 8 indicates that the value of  $A_L/A_r$  giving a minimum total-pressure loss increases from 0.502 for cold flow to 0.602 for a combustor outlet-to-inlet temperature ratio  $T_o/T_i$  of 4. The experimental data (fig. 6) show that with this configuration the total-pressure-loss coefficient at  $T_o/T_i$  of 3 is more than twice that at cold flow ( $T_o/T_i = 1$ ) conditions. Also, an increase in temperature ratio  $T_o/T_i$  increases the effect of  $M_r$  on  $\Delta P/q_r$ .

Similarly to cold-flow tests, variations in reference Reynolds number  $Re_r$  for the ranges indicated in figure 6 had no apparent effect on  $\Delta P/q_r$ . Reynolds number calculations were based on inlet conditions and the reference area  $A_r$ .

Theoretical  $\Delta P/q_r$  curves for the same configuration are included in figure 6. In the  $M_r$  range from zero to 0.05, the short dashed lines represent values of  $\Delta P/q_r$  calculated for incompressible flow with  $T_o/T_i$  of 2 and 3 (ref. 8). In this  $M_r$  range, figure 4(f) shows that the effect of compressibility on  $\Delta P/q_r$  with this configuration is small. For  $M_r$  greater than 0.06 the theoretical curves were calculated by the method of reference 3, which determines only the increase in total-pressure loss (over cold-flow conditions) resulting from heat addition.

An extrapolation of the experimental  $\Delta P/q_r$  curves for  $T_o/T_i$  of 2 and 3 to a  $M_r$  of less than 0.05 would indicate that the values of  $\Delta P/q_r$  predicted by reference 8 are somewhat lower than experimental values. For  $M_r$  greater than 0.05,  $\Delta P/q_r$  values calculated by the method of reference 3 show good agreement with most of the experimental data.

4179 In preliminary tests, abnormally high  $\Delta P/q_r$  values and flame instability at increasing fuel-air ratios were experienced with a configuration having an  $A_L/A_r$  of 0.602 and an  $A_{h,t}/A_r$  of 1.51. During these tests the combustion process was rough and noisy, and flame ejection from the upstream liner air-entry holes into the annular passage was observed. Subsequent reduction in the value of  $A_{h,t}/A_r$  from 1.51 to 1.14 resulted in reasonable  $\Delta P/q_r$  values for tests at  $M_r$  greater than 0.06 but still abnormally high  $\Delta P/q_r$  values at  $M_r$  less than 0.06 (fig. 6). Observed factors resulting in flame ejection and abnormally high pressure losses were (1) high values of  $T_o/T_i$ , (2) high values of  $A_{h,t}/A_r$ , and (3) low values of  $M_r$ .

A better understanding of the causes for the abnormally high pressure losses may be gained from a study of the effect of these factors on the static-pressure drop across the liner upstream air-entry holes. For this study a theoretical pressure distribution of a combustor liner and annulus ( $A_L/A_r = 0.60$ ,  $A_{h,t}/A_r = 1.09$  and  $M_r = 0.09$ ) from reference 8 is reproduced in figure 7. The pressure trends shown in figure 7 have been confirmed by unpublished experimental data. The relative magnitude of the static-pressure drop across a liner wall opening, at a given station along the combustor length, is indicated by the difference between curves of  $p_A/P_1$  and  $p_L/P_1$ . Curves of  $p_L/P_1$  are presented for both cold-flow conditions ( $T_o/T_i = 1$ ) and for temperature ratio  $T_o/T_i$  of 3. From figure 7 it is evident that an increase in temperature ratio  $T_o/T_i$  decreases the static-pressure drop across the liner upstream air-entry holes. Regarding the second factor,  $A_{h,t}/A_r$ , reference 8 shows that, although there is only a small change in  $\Delta P/q_r$  with increased  $A_{h,t}/A_r$  (above 1.0), there is an appreciable reduction in this static-pressure drop. As to the third factor, calculations show that reduction in  $M_r$  below the value of 0.09 for figure 7 also results in reduced static-pressure drop. Thus, a combination of large  $T_o/T_i$ , large  $A_{h,t}/A_r$ , and low  $M_r$  might not only tend to reduce the air entered



through the upstream holes to zero but may cause reverse flow and hence flame ejection. Pressure fluctuations caused by unsteady combustion would also be expected to promote flame ejection. The abnormally high pressure loss  $\Delta P/q_r$  associated with the observed flame ejection apparently results from recirculation of, and heat addition to, the gases in the annular passage.

#### Significance of Results to Combustor Design

The results of a previous theoretical analysis and of the present investigation show the effects of a number of geometric and flow variables on the total-pressure-loss coefficient of a parallel-wall turbo-jet combustor having air-entry holes in the liner wall only. The studies indicate optimum values of design parameters for minimum pressure-loss characteristics. The final design of a combustor assembly, however, is usually a compromise between aerodynamic efficiency and combustion performance.

The results of previous theoretical analyses, experimental combustor performance studies, and the present investigation suggest that the quantity  $A_r$  should be large from considerations of both combustion and aerodynamic efficiency. Increases in  $A_r$  result in decreases in  $M_r$ , which, in turn, result in higher combustion efficiencies and lower values of both the total-pressure-loss coefficient  $\Delta P/q_r$  and the percent total-pressure loss  $\Delta P/P_1$ . The liner cross-sectional area  $A_L$  should also be large in order to minimize the flame-quenching effect of the liner walls (ref. 9). From pressure-loss considerations, the optimum ratio of these two quantities ( $A_L/A_r$ ) should equal approximately 0.6. Available design data for conventional combustors indicate  $A_L/A_r$  ratios generally in the range from 0.55 to 0.60.

The selection of an optimum value of  $A_{h,t}/A_r$  will also generally be a compromise between pressure-loss considerations and combustion performance. Theoretical analyses and experimental cold-flow data (fig. 5) show that minimum pressure losses are obtained with values of  $A_{h,t}/A_r$  greater than 1.0. Experimental hot-flow data (fig. 6) obtained with  $A_{h,t}/A_r$  of 1.14 show that at high reference Mach numbers the pressure loss corresponded to calculated values, but at low  $M_r$  the  $\Delta P/q_r$  was abnormally high because of flame ejection from the upstream end of the combustion zone. Also, the maximum temperature ratio attainable was less than 4. While a decrease in  $A_{h,t}/A_r$  would probably have resulted in improved combustion performance and stability, the pressure-loss coefficient  $\Delta P/q_r$  would have increased as indicated in figure 5.

Combustion performance may also be improved by varying the distribution of air admission hole area along the liner; this would have only a small effect on  $\Delta P/q_r$  (fig. 4(h)). The problems of supplying sufficient air to the primary zone to permit operation at high temperature ratios, and of avoiding flame ejection from the primary zone when using large values of  $A_{h,t}/A_r$  might be alleviated in one of two ways: (1) the use of scoops or louvres in the annular air passage surrounding the combustion zone, or (2) the use of "snouts" or "splitter plates" in the diffuser section in order to supply all air required for the combustion process from regions of relatively high static pressure.

### CONCLUSIONS

Experimental and theoretical total-pressure losses of a turbojet-engine combustor were compared. Calculated values of cold-flow total-pressure-loss coefficient that include annulus wall friction were generally higher than (but within 17 percent of) the experimental values. Better agreement with experimental data was shown by calculated values that neglected annulus wall friction. The comparison indicates that a reasonable estimate of cold-flow total-pressure-loss coefficient may be obtained from the generalized curves or from the method of calculation presented in reference 8. Calculated values of total-pressure-loss coefficient due to heat addition alone show good agreement with the experimental data if there is no flame ejection from the liner at the upstream air-entry holes. With flame ejection the total-pressure-loss coefficient was abnormally high because of recirculation of, and heat addition to, the gases in the annular passage. Observed factors causing flame ejection were (1) relatively large liner total hole area, (2) a large outlet-to-inlet temperature ratio, and (3) a low reference Mach number.

Lewis Flight Propulsion Laboratory  
National Advisory Committee for Aeronautics  
Cleveland, Ohio, September 17, 1956

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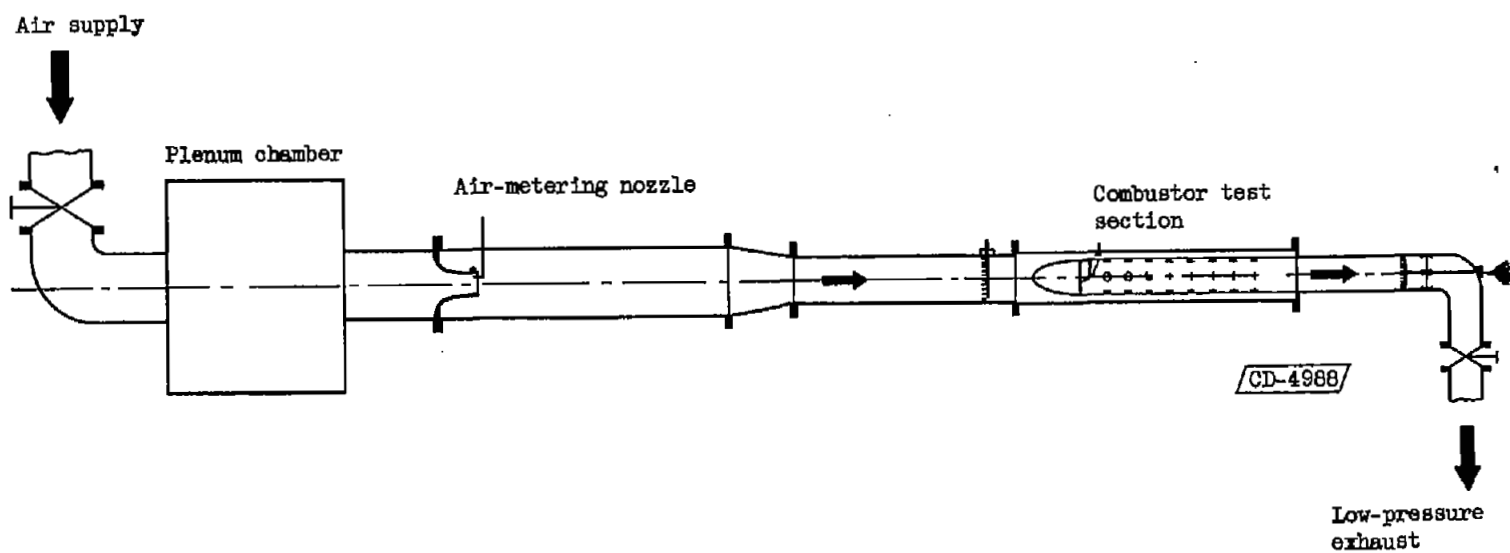


Figure 1. - Research combustor installation for total-pressure-loss study.

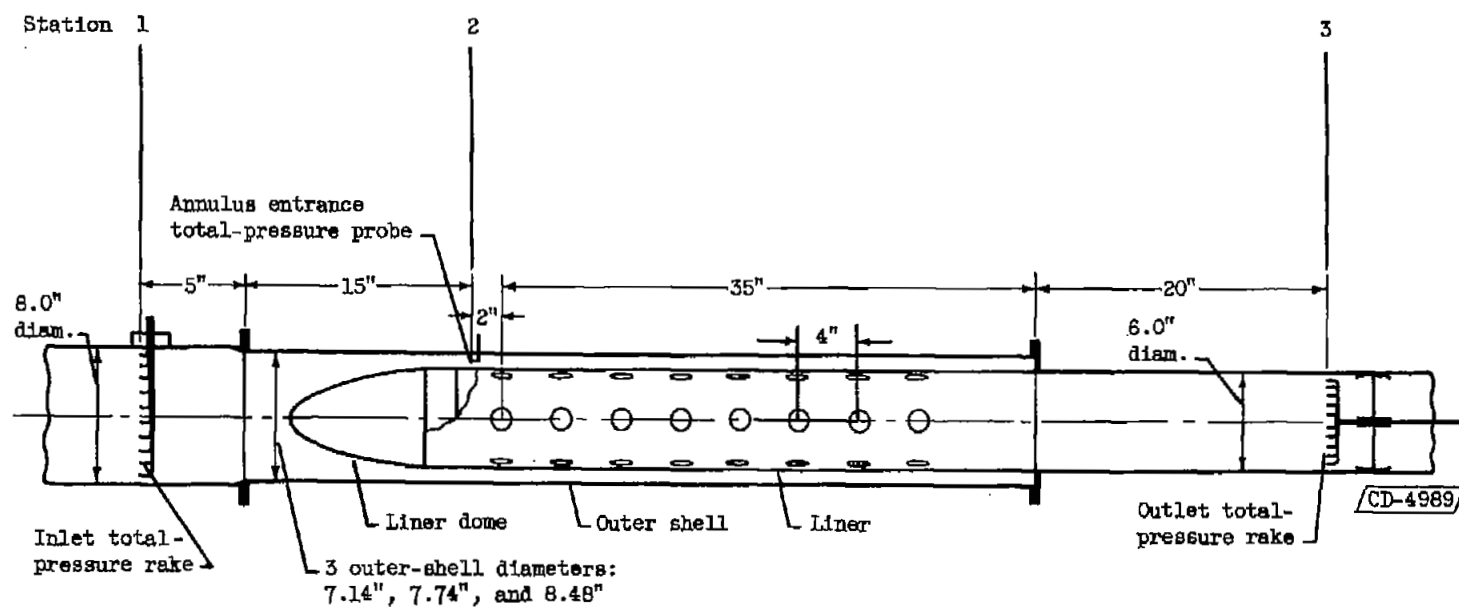


Figure 2. - Details of research combustor (cold flow).

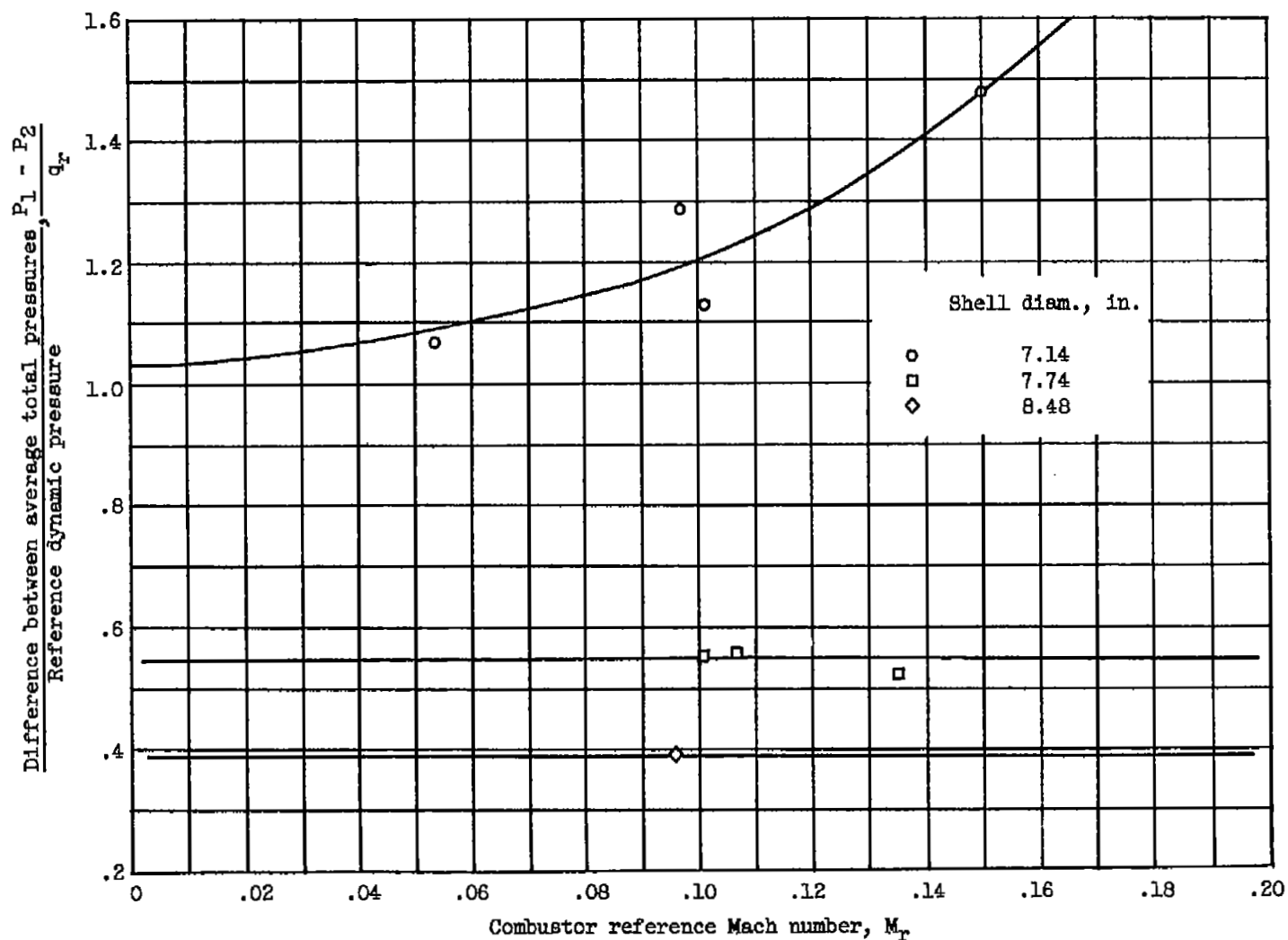
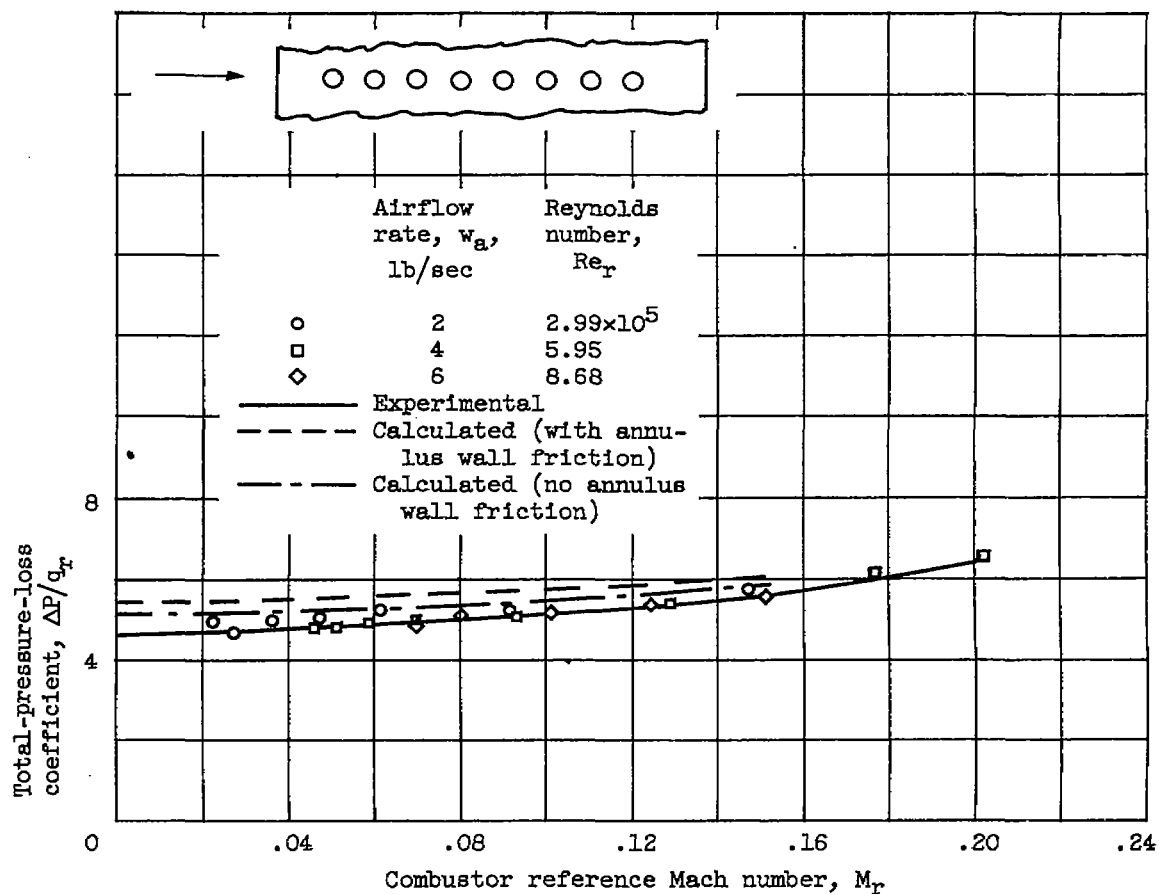
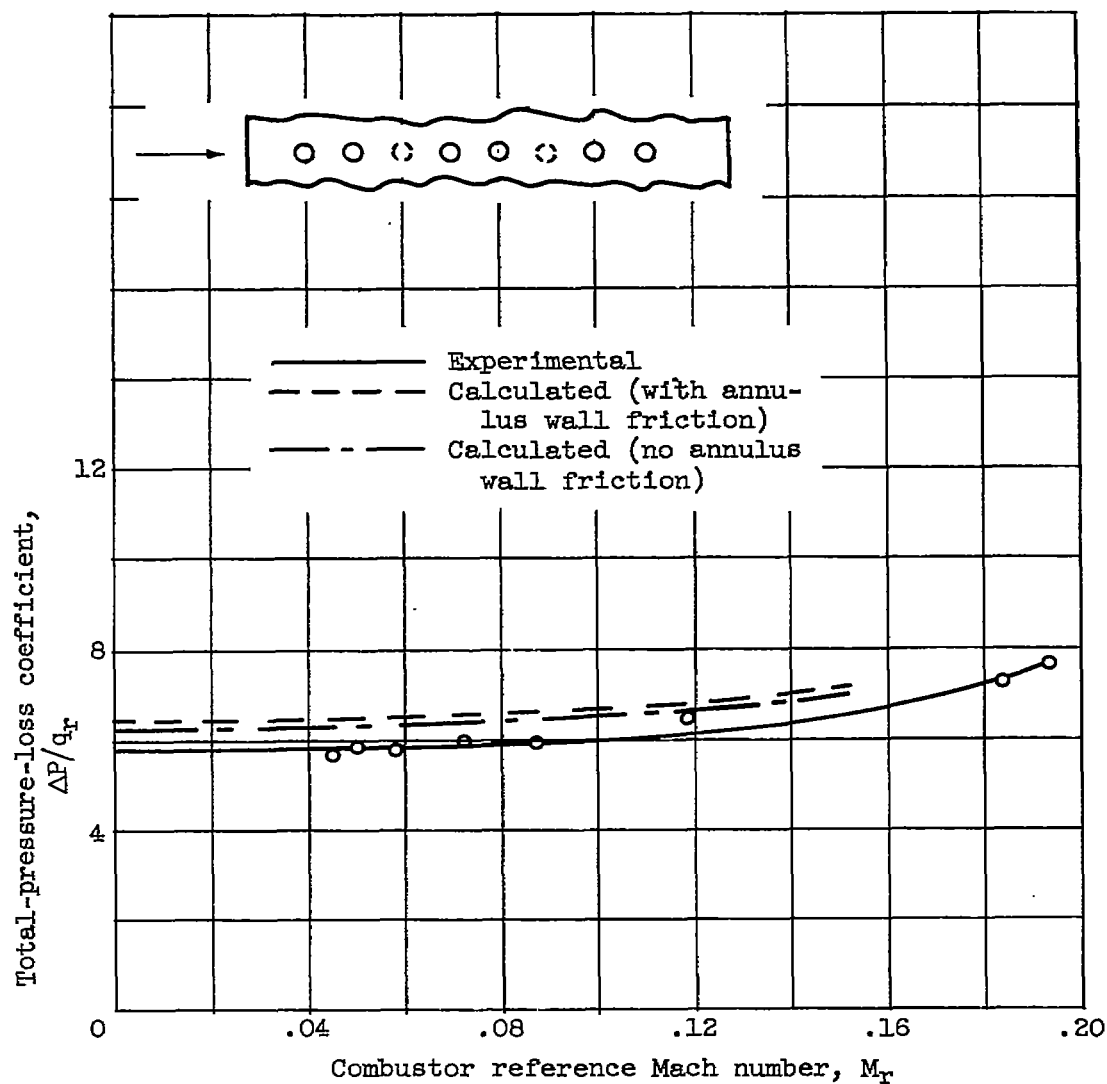


Figure 3. - Variation in average total-pressure-loss coefficient between stations 1 and 2 with reference Mach number for various diameter outer shells.



(a)  $A_L/A_r = 0.502$ ;  $A_{h,t}/A_r = 1.26$ .

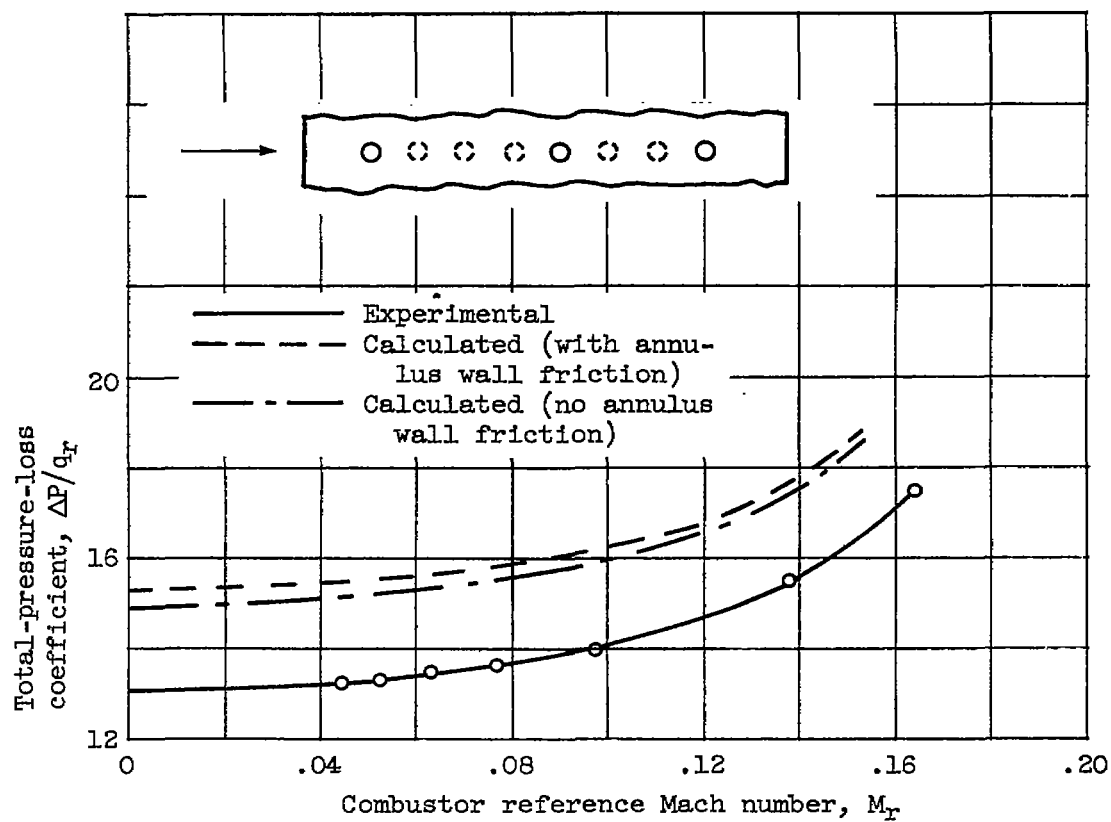
Figure 4. - Variation of pressure-loss coefficient with reference Mach number at cold-flow conditions.



(b)  $A_L/A_r = 0.502$ ;  $A_{n,t}/A_r = 0.95$ .

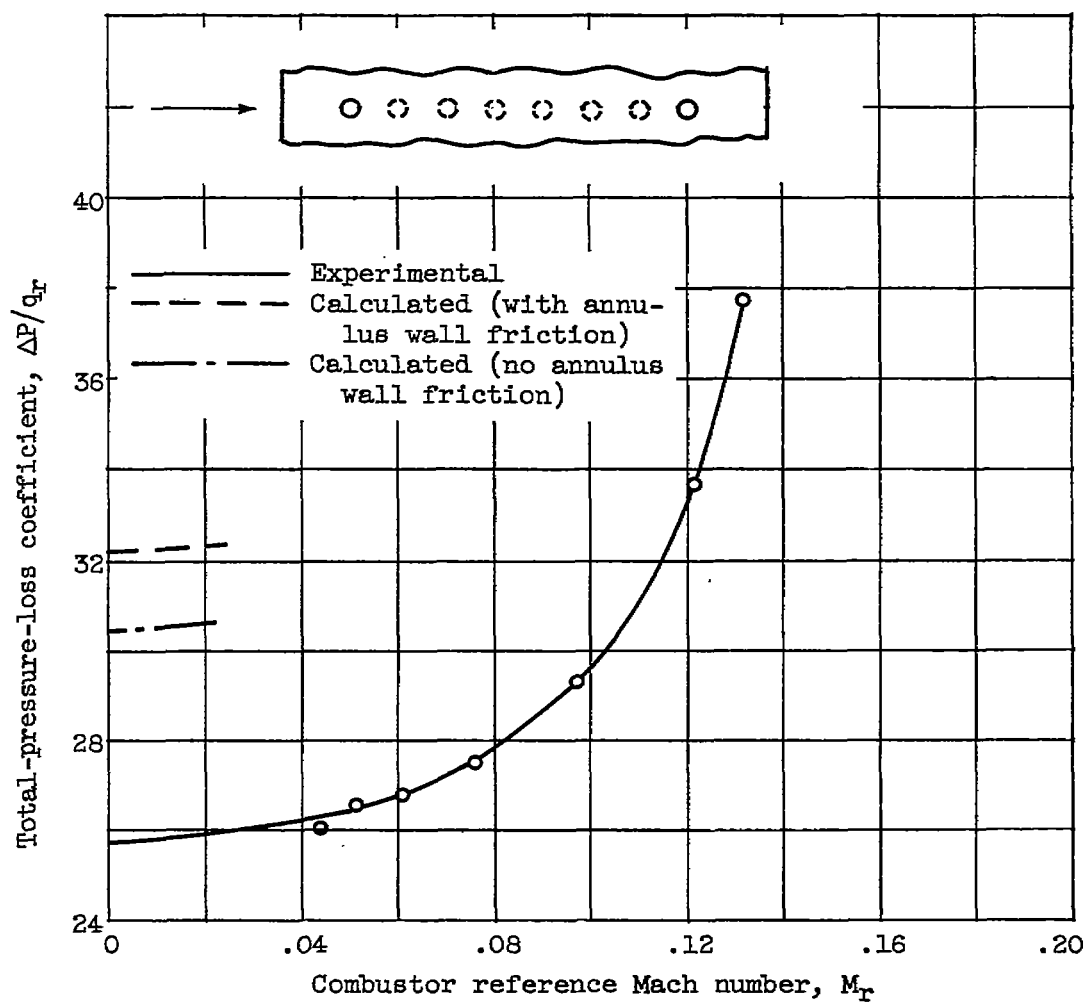
Figure 4. - Continued. Variation of pressure-loss coefficient with reference Mach number at cold-flow conditions.





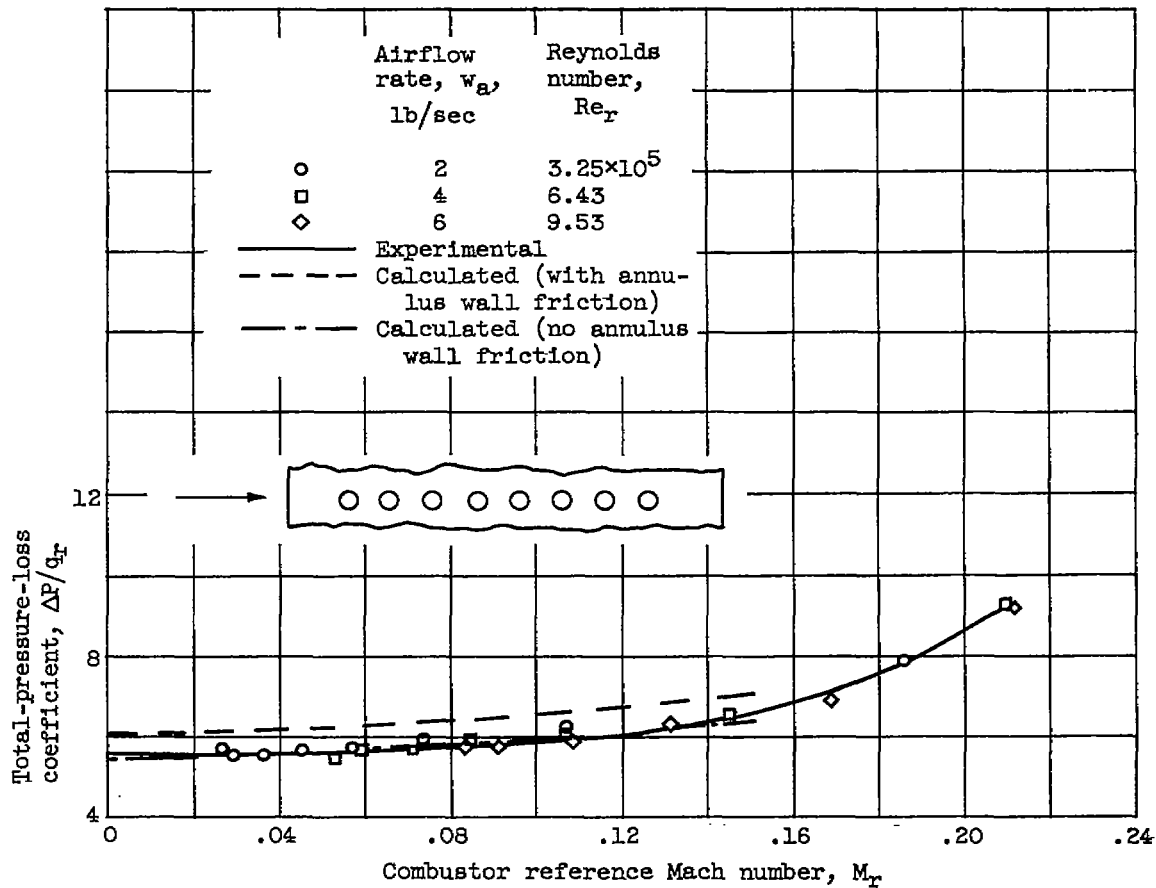
(c)  $A_L/A_r = 0.502$ ;  $A_{h,t}/A_r = 0.47$ .

Figure 4. - Continued. Variation of pressure-loss coefficient with reference Mach number at cold-flow conditions.



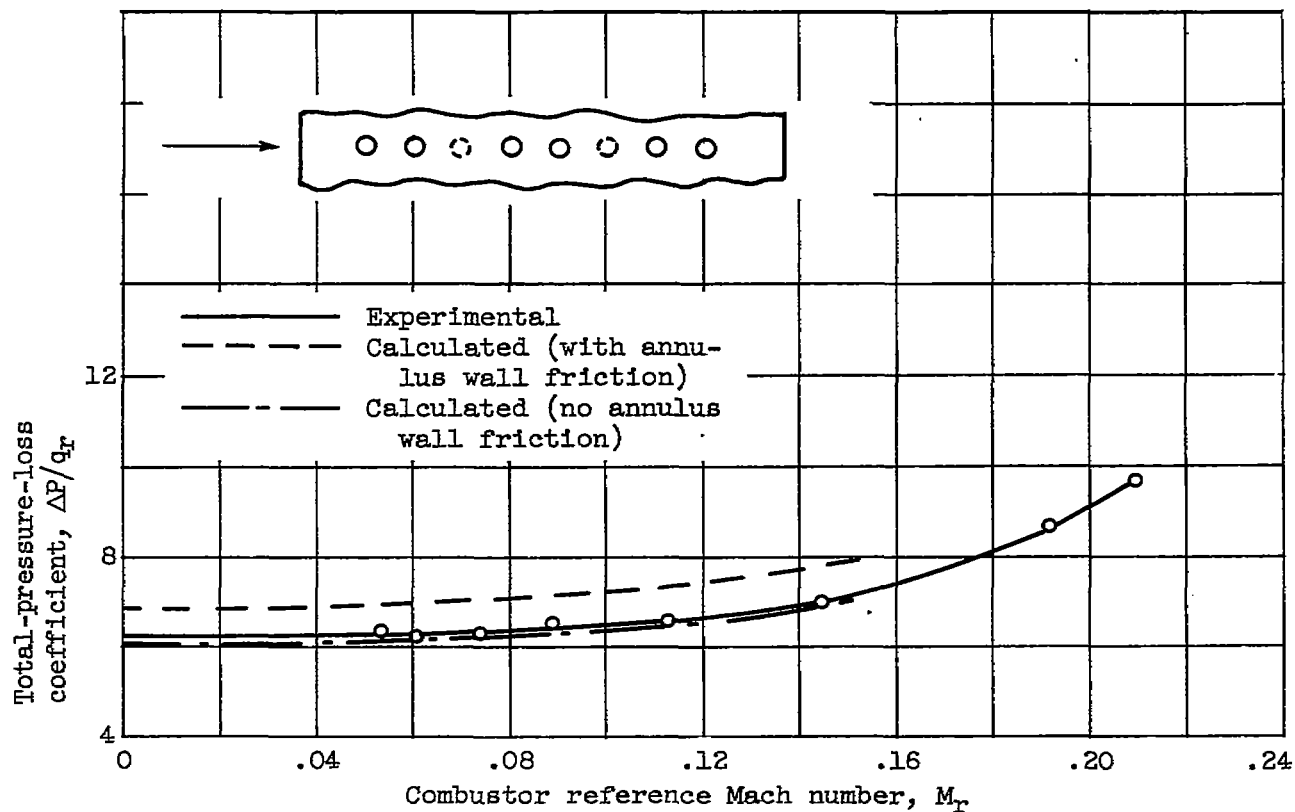
(d)  $A_L/A_T = 0.502$ ;  $A_{h,t}/A_T = 0.32$ .

Figure 4. - Continued. Variation of pressure-loss coefficient with reference Mach number at cold-flow conditions.



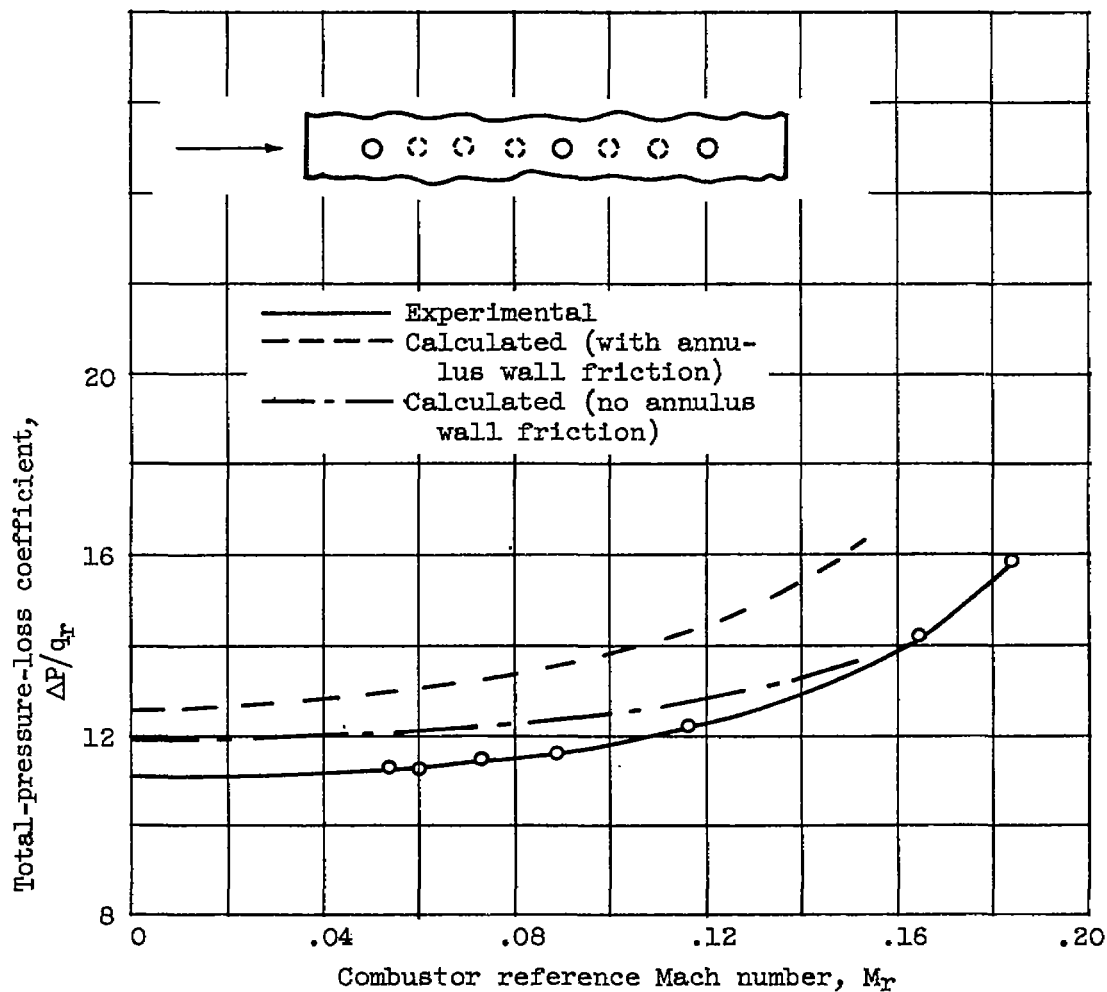
(e)  $A_I/A_T = 0.602$ ;  $A_{h,t}/A_T = 1.51$ .

Figure 4. - Continued. Variation of pressure-loss coefficient with reference Mach number at cold-flow conditions.



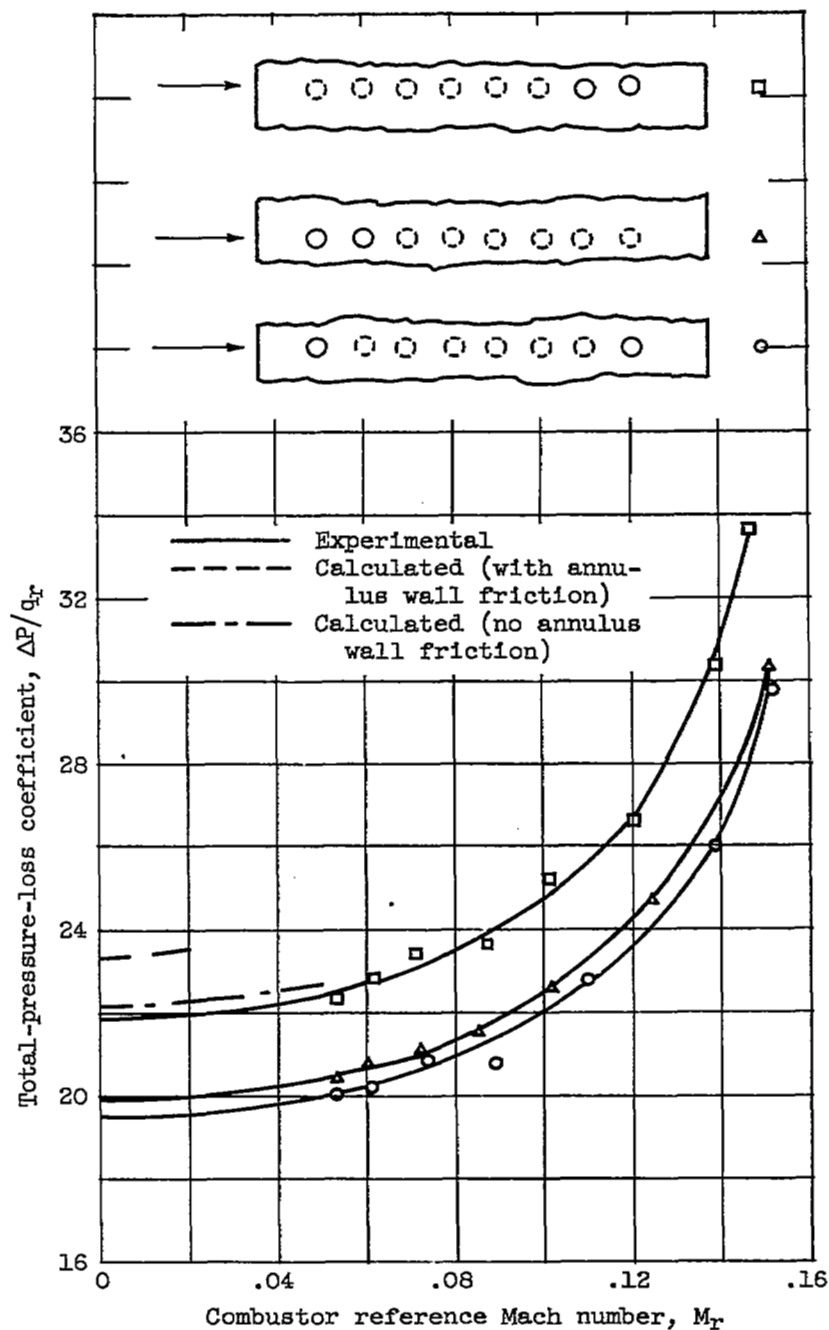
(f)  $A_L/A_R = 0.602$ ;  $A_{h,t}/A_R = 1.14$ .

Figure 4. - Continued. Variation of pressure-loss coefficient with reference Mach number at cold-flow conditions.



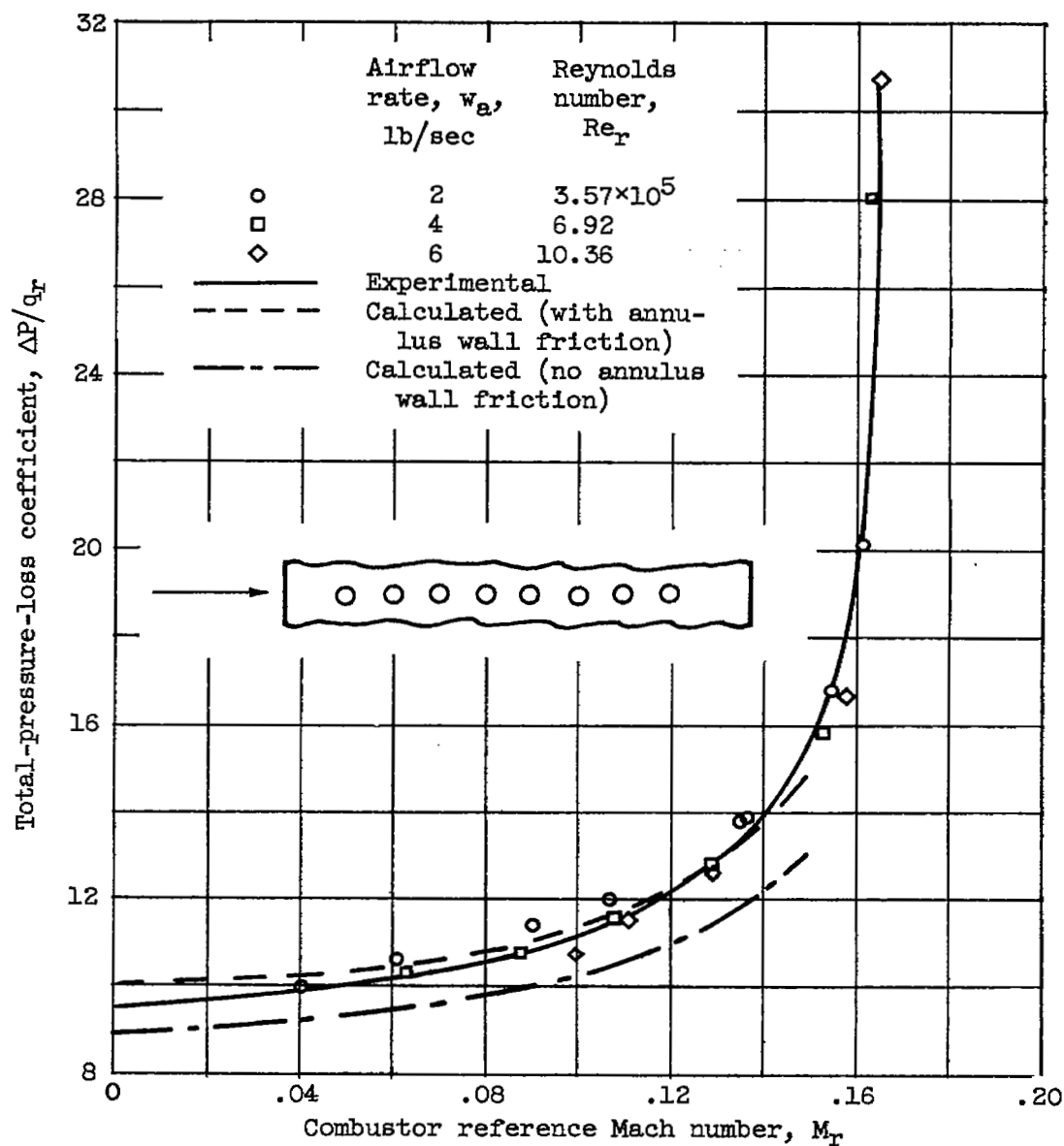
(g)  $A_L/A_r = 0.602$ ;  $A_{h,t}/A_r = 0.57$ .

Figure 4. - Continued. Variation of pressure-loss coefficient with reference Mach number at cold-flow conditions.



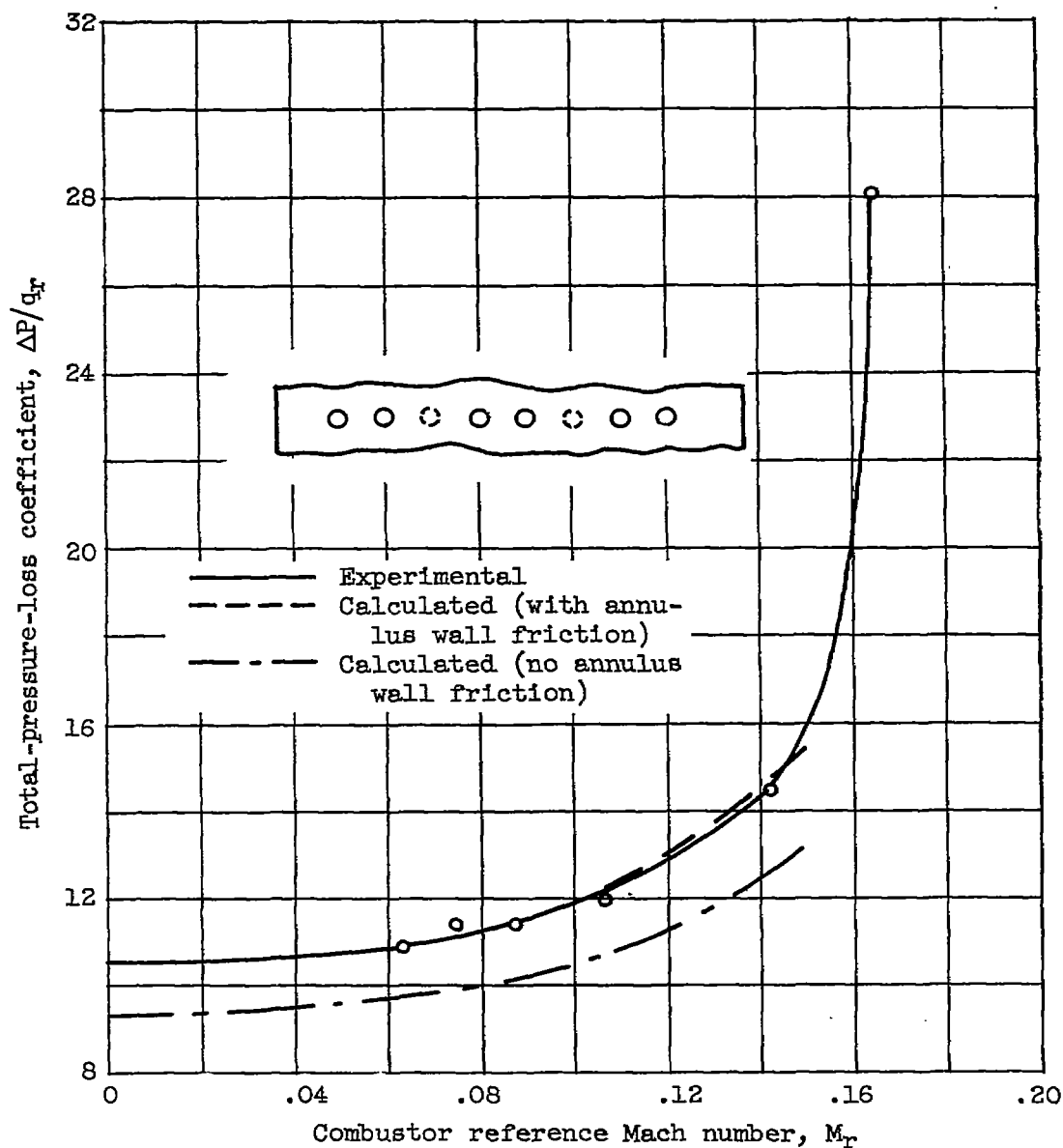
(h)  $A_L/A_r = 0.602$ ;  $A_{h,t}/A_r = 0.38$ .

Figure 4. - Continued. Variation of pressure-loss coefficient with reference Mach number at cold-flow conditions.



(1)  $A_L/A_r = 0.708$ ;  $A_{h,t}/A_r = 1.78$ .

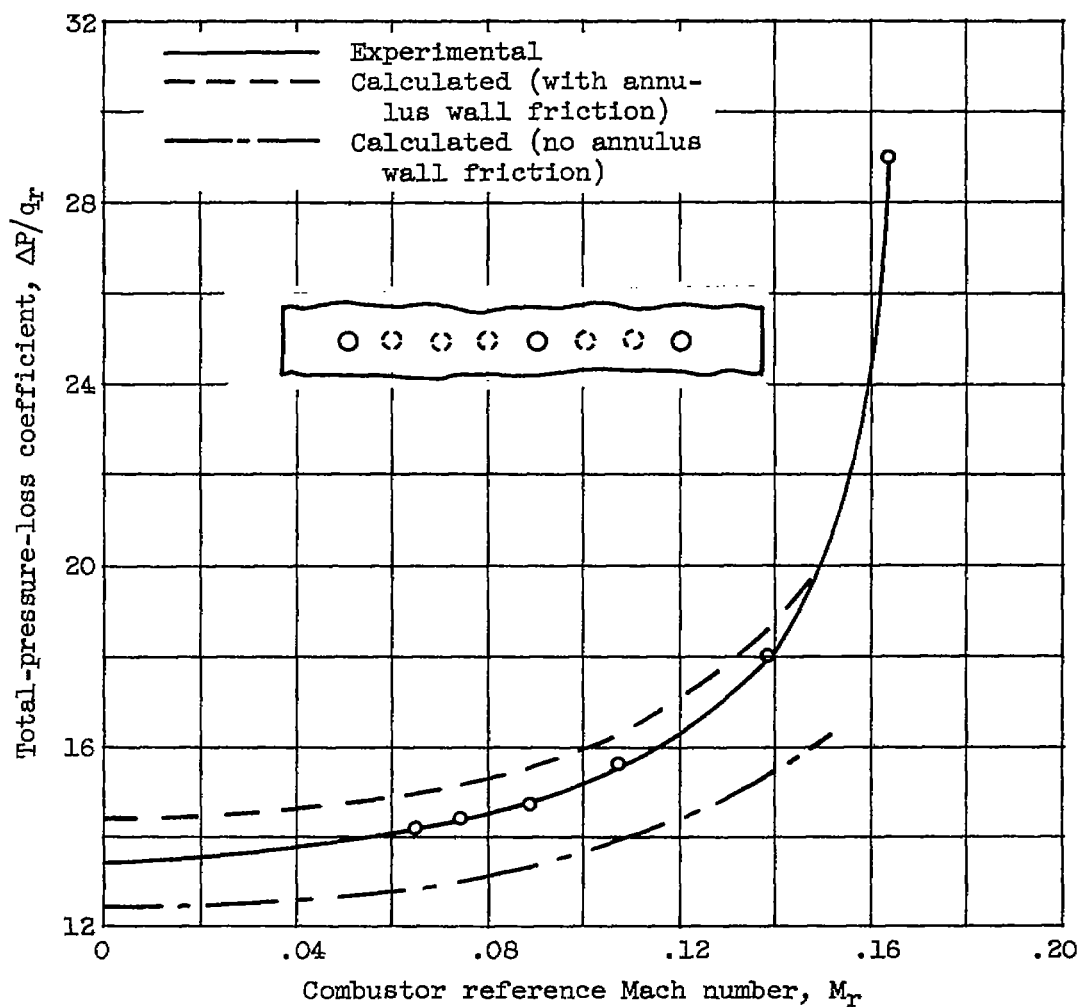
Figure 4. - Continued. Variation of pressure-loss coefficient with reference Mach number at cold-flow conditions.



(j)  $A_L/A_r = 0.708$ ;  $A_{h,t}/A_r = 1.34$ .

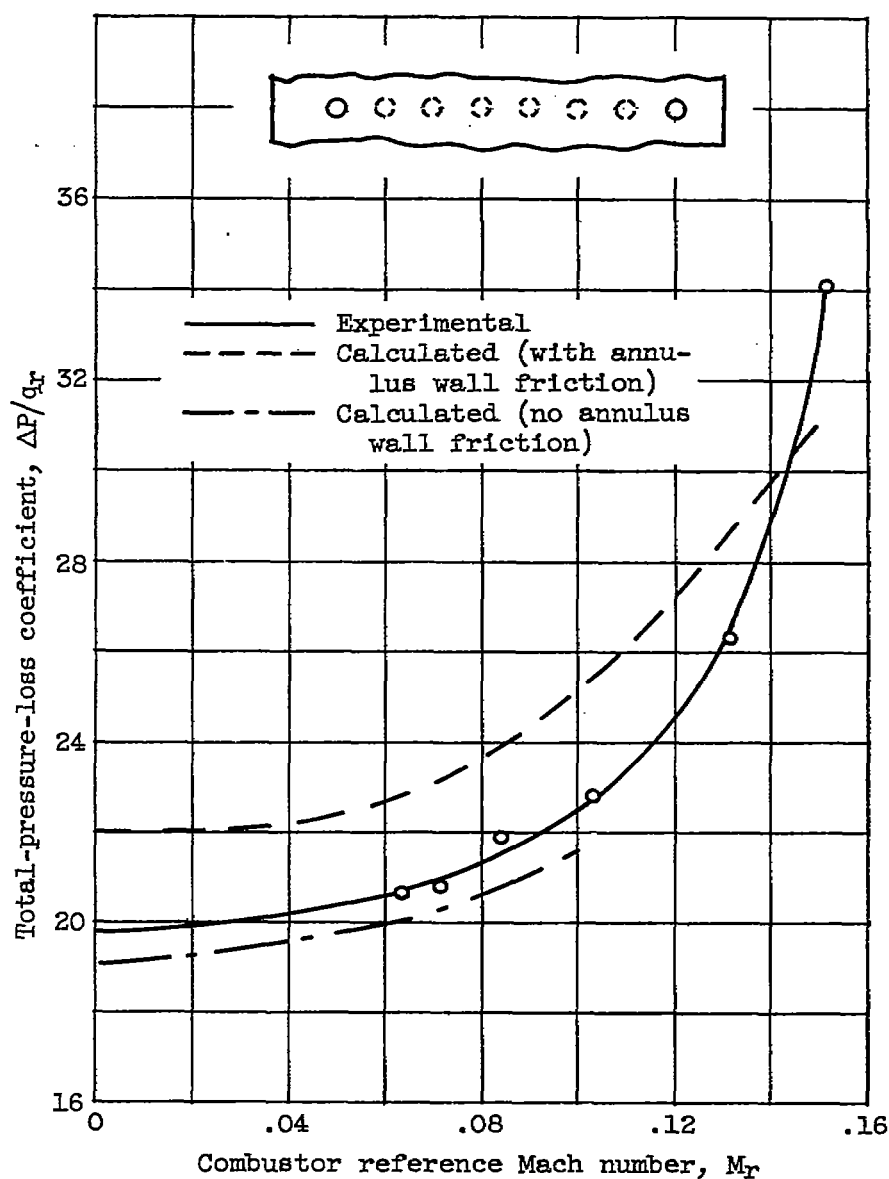
Figure 4. - Continued. Variation of pressure-loss coefficient with reference Mach number at cold-flow conditions.





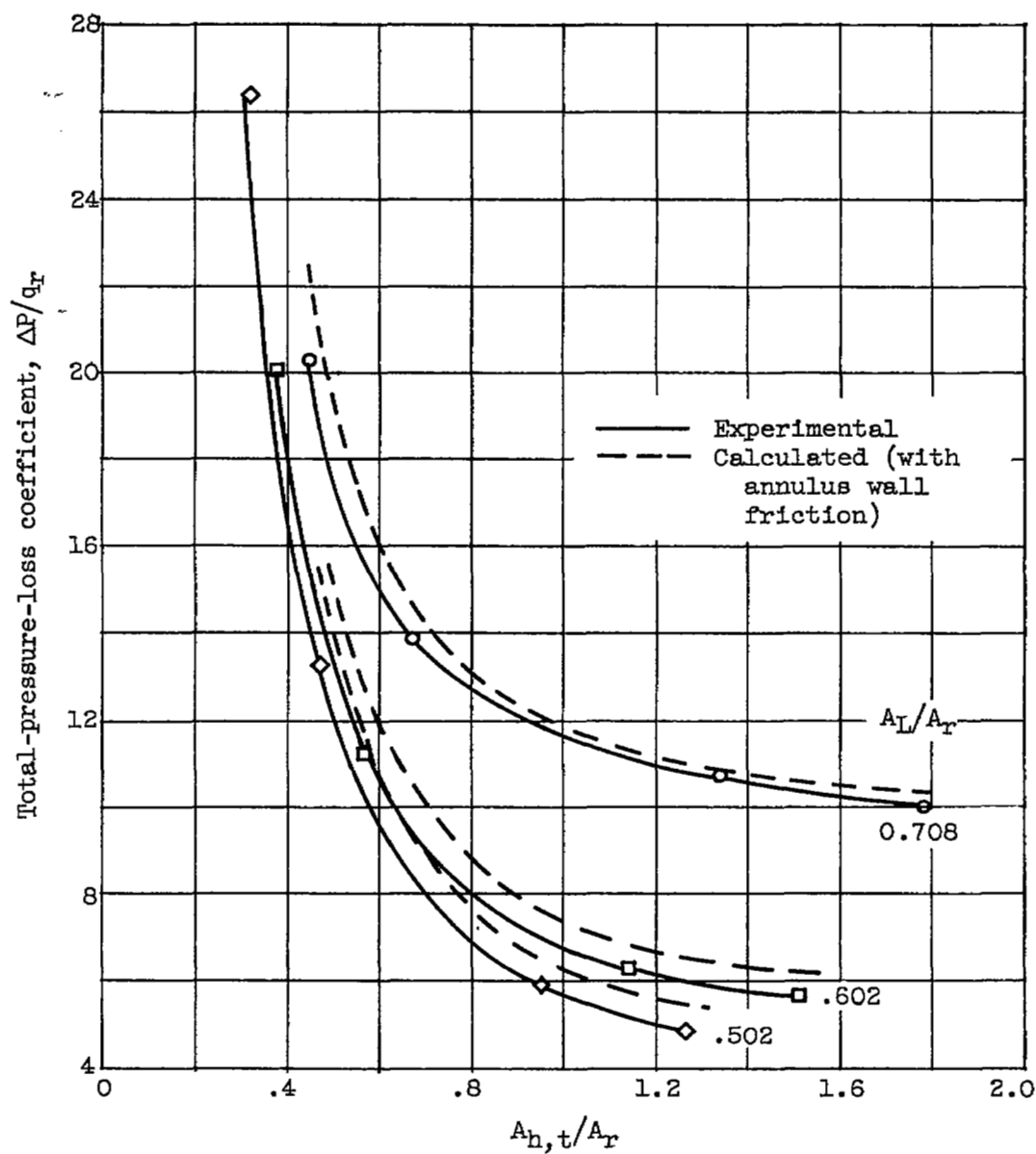
(k)  $A_I/A_r = 0.708$ ;  $A_{h,t}/A_r = 0.67$ .

Figure 4. - Continued. Variation of pressure-loss coefficient with reference Mach number at cold-flow conditions.



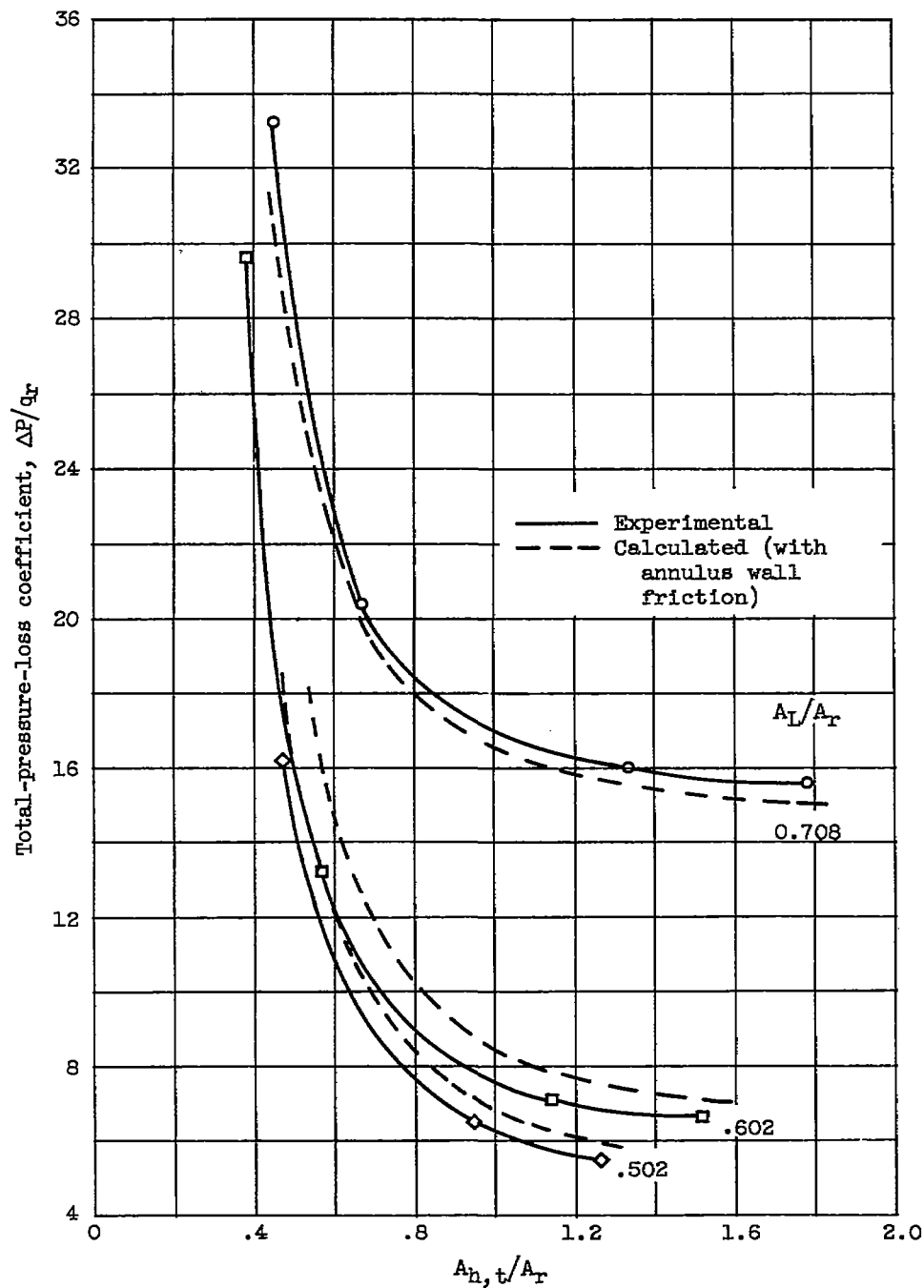
(2)  $A_L/A_R = 0.708$ ;  $A_{h,t}/A_R = 0.45$ .

Figure 4. - Concluded. Variation of pressure-loss coefficient with reference Mach number at cold-flow conditions.



(a) Combustor reference Mach number, 0.05.

Figure 5. - Variation of pressure-loss coefficient with design parameters at cold-flow conditions.



(b) Combustor reference Mach number, 0.15.

Figure 5. - Concluded. Variation of pressure-loss coefficient with design parameters at cold-flow conditions.

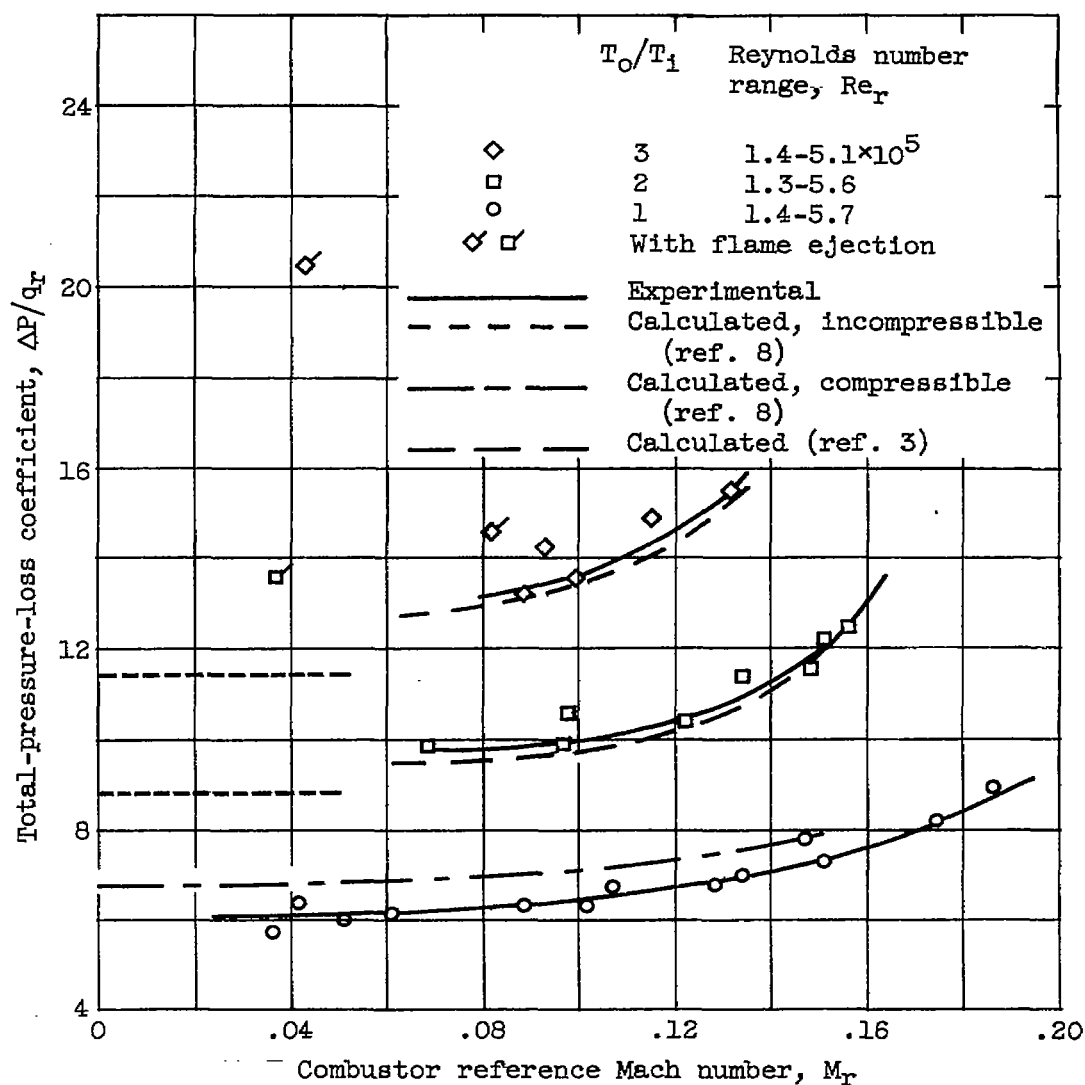


Figure 6. - Variation of pressure-loss coefficient with reference Mach number at hot-flow conditions for a configuration having a liner area ratio  $A_L/A_r$  of 0.602 and a total open hole area ratio  $A_{h,t}/A_r$  of 1.14.

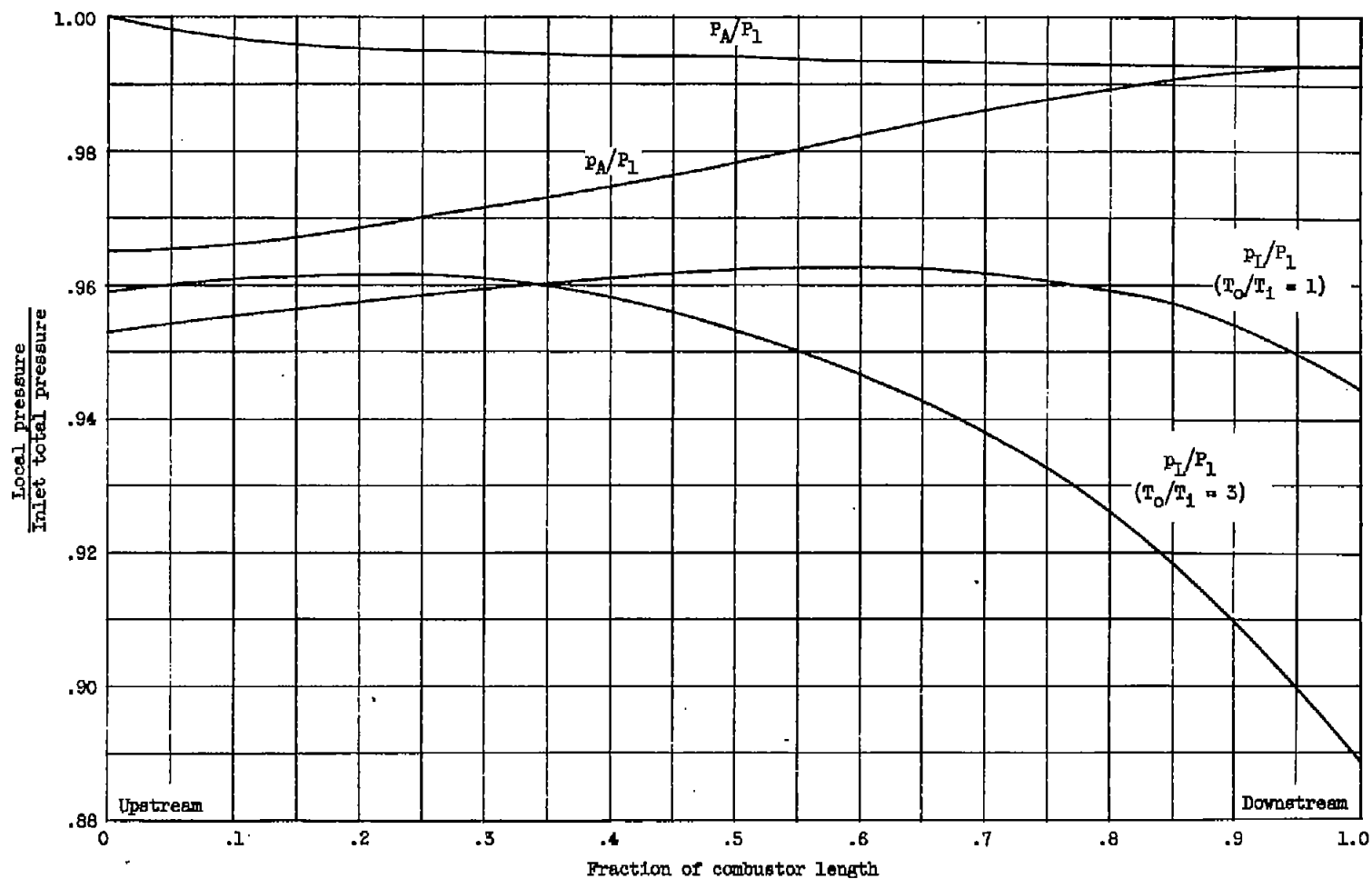


Figure 7. - Pressure distribution in annulus and liner of a combustor having  $A_t/A_r$  of 0.60,  $A_{h,t}/A_r$  of 1.09, and  $M_r$  of 0.09 at two temperature ratios.



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